Constraints on the time variation of the gravitational constant using gravitational-wave observations of binary neutron stars

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Background

Many alternative theories of gravity, e.g., scalar-tensor theories like Brans-Dicke theory **predict a time-varying gravitational "constant"** G. We use gravitational-wave (GW) observations of binary neutron (BNS) stars to constrain the time-variation of G.

The maximum and minimum allowed masses of neutron stars ($m_s^{\text{min, max}}$) at a particular cosmic epoch has a **simple dependence on the value of** $G = G_s$ **at that epoch,**

$$m_s^{\text{min, max}} = m^{\text{min, max}} \, (G_s/G_o)^{-3/2} \tag{1}$$

where G_o is the current value of G, and $m^{\text{min, max}}$ is the current value of minimum and maximum mass for the neutron stars.

Let m_o be the measured (source-frame) mass. The template matching condition gives,

$$m_o = \frac{G_s}{G_o}\left(\frac{1+z_s}{1+z_o}\right) m_s \tag{2}$$

where z_s is the true cosmological redshift of the source and z_o is the estimated redshift, say, from an electromagnetic observation.

Using the above equations, we can derive the bounds within which the observed masses should lie,

$$m_o^{\text{max, min}} = m^{\text{max, min}} \, (G_s/G_o)^{-1/2}. \tag{3}$$

That is, when $G_s \neq G_o$, the allowed range of measured NS masses will be different from the range m^{min} — m^{max}. If G_s has a significant deviation from the current value G_o, the **observed values of NS masses would have gone out of the allowed range of NS masses**. Hence such **large deviations are ruled out by current GW observations** [illustrated in Figure [2] using conservative estimates for m^{min}—m^{max} ($0.09M_\odot$—$4M_\odot$)].

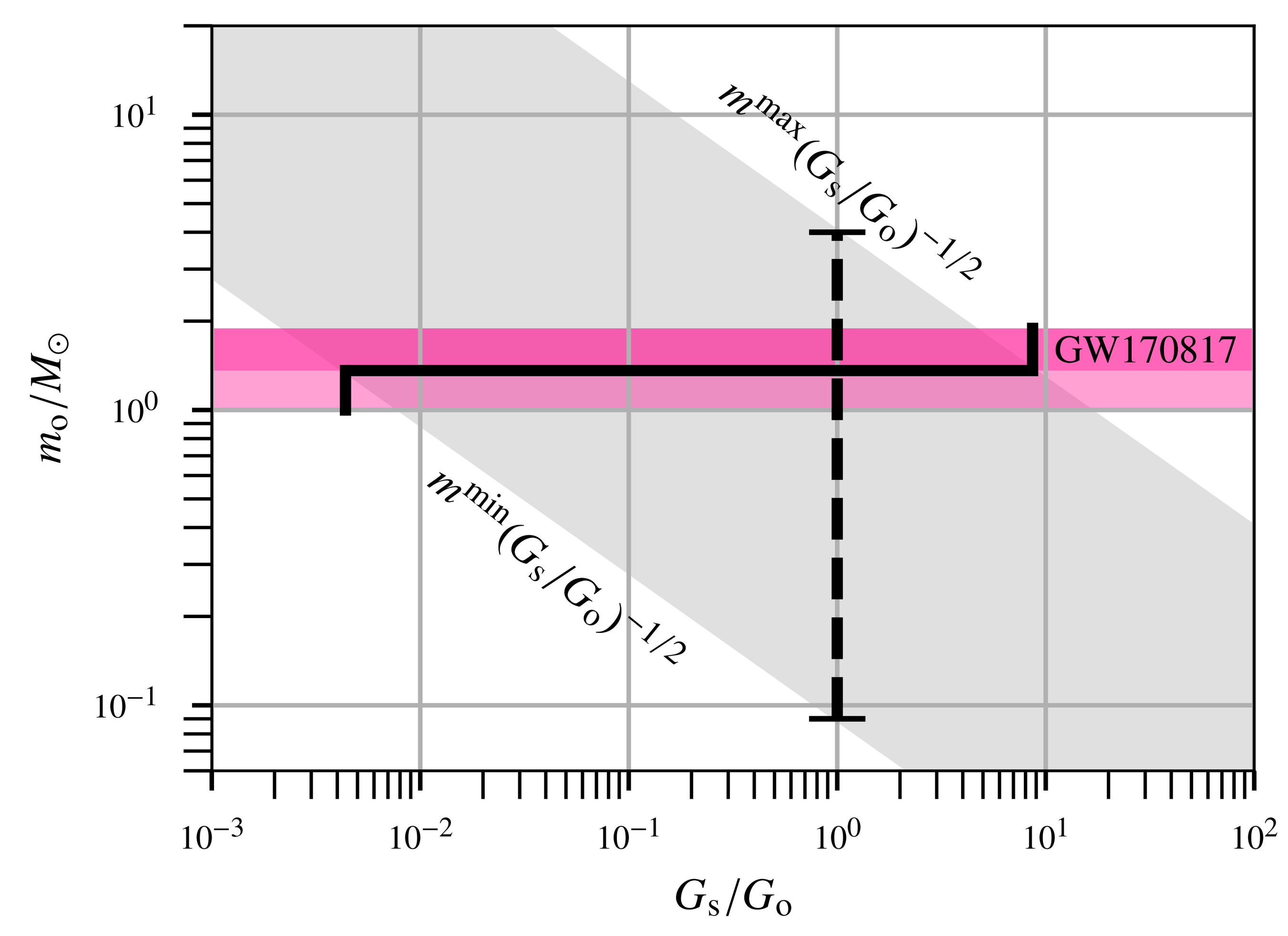

Fig. 2: ***Horizontal axis****: assumed value of G_s/G_o at the BNS merger epoch;* ***Vertical axis****: measured value of the neutron star mass $m_o/M_\odot$;* ***Horizontal patches****: measured value of the neutron star masses from GW170817 (90% credible regions; dark shade is primary mass, light shade is secondary mass);* ***Vertical dashed lines****: theoretically allowed range of neutron star masses $m^{\text{min}} - m^{\text{max}}$ ($0.09M_\odot - 4M_\odot$) at the current epoch.* ***Tilted gray regions****: allowed range of the observed neutron star mass (eq. [3]).* ***Horizontal error bars****: constraints on G_s/G_o by requiring that the measured values overlap with the theoretically allowed (gray) region.*

Results

- When $G_s \lesssim 4\times10^{-3}G_o$ or when $G_s \gtrsim 9G_o$, the observed mass range of the NSs in GW170817 will go out of the predicted mass range. Thus, the fractional deviation $\Delta G/G_o := (G_s - G_o)/G_o$ in gravitational constant is constrained to be:

$$\boxed{-0.996 \lesssim \Delta G/G_o \lesssim 8}$$

- If we know the time Δt elapsed between merger and GW observation, we can compute an average rate of change of the G during this period: $\dot{G}/G_o \simeq \Delta G/(G_o \Delta t)$. For GW170817, we infer:

$$\boxed{-7\times10^{-9}\ \text{yr}^{-1} \lesssim \dot{G}/G_o \lesssim 5\times10^{-8}\ \text{yr}^{-1}}$$

Summary and Future Directions

- Although our constraints are not as tight as the best available bounds from other measurements, they sample a different cosmological epoch that is not covered by other observations.
- Gravitational-wave observations sampling the extremes of the neutron star masses will further tighten these bounds.
- Additional detections of binary neutron stars would constrain the variation of G at different epochs. Projected constraints from third-generation GW detectors are shown in Figure [1].

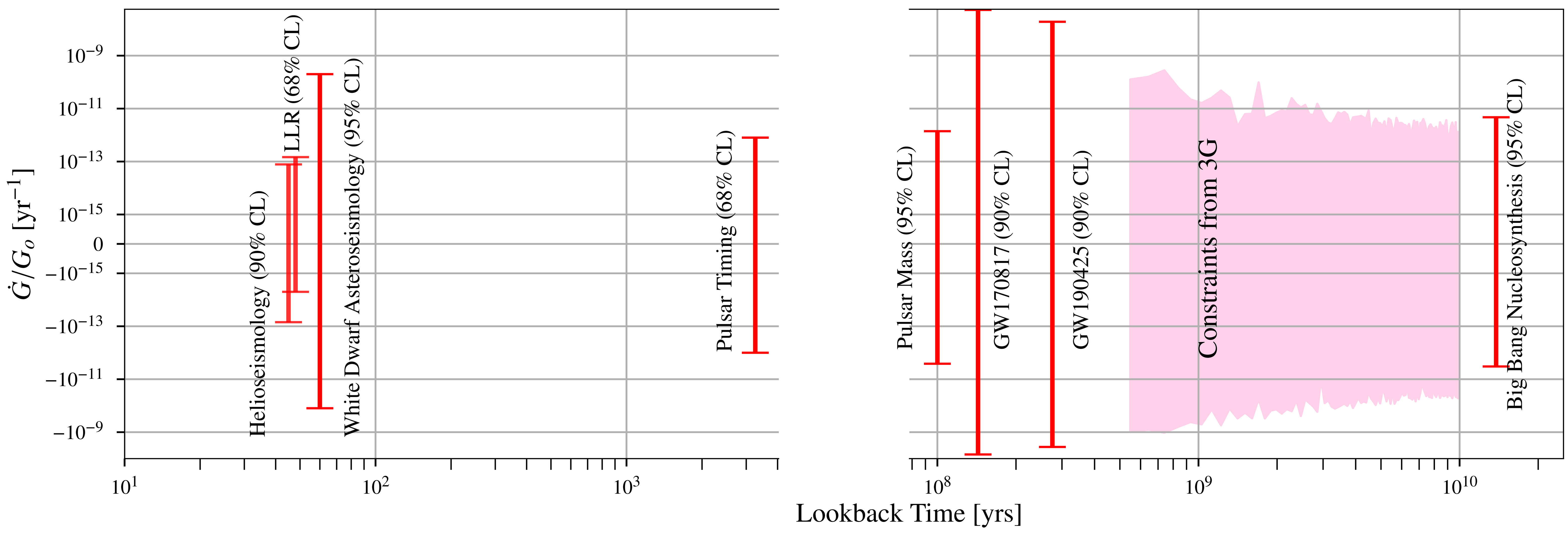

Fig. 1: Comparison of the constraints on $\dot{G}/G_o$ obtained from various observations with confidence levels of the constraints indicated in brackets (LLR denotes constraints from lunar laser ranging). The horizontal axis shows the look back time. The constraints presented this paper are labeled as GW170817 and GW190425, while the expected constraints from 10 year of observations with third-generation (3G) GW detectors is shown by the pink band.